XSUSY
A multipurpose program for calculations in SUSY models with non-minimal flavour violation

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Outline

1. SUSY models with non-minimal flavour violation
   - Constrained minimal flavour violation
   - Non-minimal flavour violation (NMFV)
   - Tools needed for a complete NMFV study
2. Description of XSUSY
   - The XSUSY approach
   - The XSUSY core: cross sections and decay widths
3. Examples
   - Simplified NMFV scenario
   - Parameter space analysis
   - Flavour structure analysis
   - Production cross sections
   - Decay widths
4. Summary and outlook

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Constrained minimal flavour violation

[Ciuchini, Degrassi, Gambino, Giudice (1998)]

- Squared sfermion mass matrices:

$$M^2_{\tilde F} = \begin{pmatrix} M^2_{LL,1} & 0 & 0 & m_1\, m_{LR,1} & 0 & 0 \\ 0 & M^2_{LL,2} & 0 & 0 & m_2\, m_{LR,2} & 0 \\ 0 & 0 & M^2_{LL,3} & 0 & 0 & m_3\, m_{LR,3} \\ m_1\, m_{RL,1} & 0 & 0 & M^2_{RR,1} & 0 & 0 \\ 0 & m_2\, m_{RL,2} & 0 & 0 & M^2_{RR,2} & 0 \\ 0 & 0 & m_3\, m_{RL,3} & 0 & 0 & M^2_{RR,3} \end{pmatrix}$$

  * All flavour-violating elements of $M^2_{\tilde F}$ are zero.
  * Sfermion mixing: $(\tilde f_L, \tilde f_R) \Rightarrow (\tilde f_1, \tilde f_2)$ with flavour conservation.
  * Small first- and second-generation fermion masses: $m_1, m_2 \longrightarrow 0$.
  * Three flavour-conserving mixing angles, $\theta_{\tilde t}$, $\theta_{\tilde b}$ and $\theta_{\tilde \tau}$.

- Squark sector
  * Flavour violation is governed by the CKM matrix, within the interactions.
  * e.g. chargino-squark-quark vertex proportional to $V_{qq'}$.

Non-minimal flavour violation

[Gabbiani, Gabrielli, Masiero, Silvestrini (1996)]

- The squared squark mass matrices are

$$M^2_{\tilde{Q}} = \begin{pmatrix} M^2_{LL,1} & \Delta^{12}_{LL} & \Delta^{13}_{LL} & m_1\, m_{LR,1} & \Delta^{12}_{LR} & \Delta^{13}_{LR} \\ \Delta^{21}_{LL} & M^2_{LL,2} & \Delta^{23}_{LL} & \Delta^{21}_{RL} & m_2\, m_{LR,2} & \Delta^{23}_{LR} \\ \Delta^{31}_{LL} & \Delta^{32}_{LL} & M^2_{LL,3} & \Delta^{31}_{RL} & \Delta^{32}_{RL} & m_3\, m_{LR,3} \\ m_1\, m_{RL,1} & \Delta^{12}_{RL} & \Delta^{13}_{RL} & M^2_{RR,1} & \Delta^{12}_{RR} & \Delta^{13}_{RR} \\ \Delta^{21}_{LR} & m_2\, m_{RL,2} & \Delta^{23}_{RL} & \Delta^{21}_{RR} & M^2_{RR,2} & \Delta^{23}_{RR} \\ \Delta^{31}_{LR} & \Delta^{32}_{LR} & m_3\, m_{RL,3} & \Delta^{31}_{RR} & \Delta^{32}_{RR} & M^2_{RR,3} \end{pmatrix} .$$

  * The off-diagonal elements are 24 new free parameters, parameterized by
  $$\Delta^{qq'}_{ij} = \lambda^{qq'}_{ij} M_{ii,q} M_{jj,q'} .$$
  * Diagonalization through 6×6 rotation matrices R^u and R^d.

- Physical eigenstates given by

$$\begin{aligned} (\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6)^T &= R^u(\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T, \\ (\tilde{d}_1, \tilde{d}_2, \tilde{d}_3, \tilde{d}_4, \tilde{d}_5, \tilde{d}_6)^T &= R^d(\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R)^T. \end{aligned}$$

Constraints on non-minimal flavour violation

- Scaling of the off-diagonal terms with the SUSY-breaking scale:

$$\Delta_{LL} \gg \Delta_{LR,RL} \gg \Delta_{RR}$$

[Gabbiani, Masiero (1989)]

- FCNC: upper limits on λ's.
  * Neutral kaon sector (Δm_K, ε, ε'/ε)
  * B-meson oscillations,
  * D-meson oscillations (Δm_D),
  * Rare decays (BR($b \to s\gamma$), BR($\mu \to e\gamma$), BR($\tau \to e\gamma$), BR($\tau \to \mu\gamma$)),
  * Electric dipole moments (d_n and d_e).

[Gabbiani, Gabrielli, Masiero, Silvestrini (1996)]
[Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives (2007)]

- Cosmological constraints:
  * color singlet and electrically neutral LSP [Ellis *et al.* (1984)]
  * Dark matter relic density
    (WMAP, SDSS, SNLS, and Baryon Acoustic Oscillations data)
    [Hamann, Hannestad, Sloth, Wong (2007)]

Tools needed for a complete NMFV study

- Inputs
  - SM parameters.
  - Reduced number of SUSY parameters at GUT scale.
  - NMFV parameters at low-energy scale.
- Outputs:
  - Are NMFV SUSY models experimentally viable?
    $\Rightarrow$ Analysis of the allowed parameter space.
  - What is the flavour content of the physical particles?
    $\Rightarrow$ Analysis of the flavour structure in the squark sector.
  - Are hadron colliders sensible to NMFV?
    $\Rightarrow$ Dependence of the production cross sections on flavour violation.
    $\Rightarrow$ Dependence of the decay widths on flavour violation.

Existing and missing tools

- From GUT scale to EW scale
  - * Solution to the renormalization group equations.
  - * SPheno 2.2.3 [Porod (2003)], SuSpect 2.34 [Djouadi, Kneur, Moultaka (2007)],... (only constrained Minimal Flavour Violation (cMFV) scenarios.)
- Introduction of NMFV at low energy:
  - * Generalized squark mass matrices, SUSY spectrum and mixing matrices.
  - * FeynHiggs 2.5.1. [Heinemeyer, Hollik, Weiglein (2000)].
- Constraints:
  - * Low energy and EW constraints in cMFV: FeynHiggs, SPheno, SuSpect.
  - * Low energy and EW constraints in NMFV: FeynHiggs.
  - * Dark matter relic density in cMFV: DarkSUSY 4.1 [Gondolo *et al.* (2004)],...
- Missing pieces:
  - * Dark matter relic density in NMFV.
  - * Production cross sections.
  - * Decays widths.

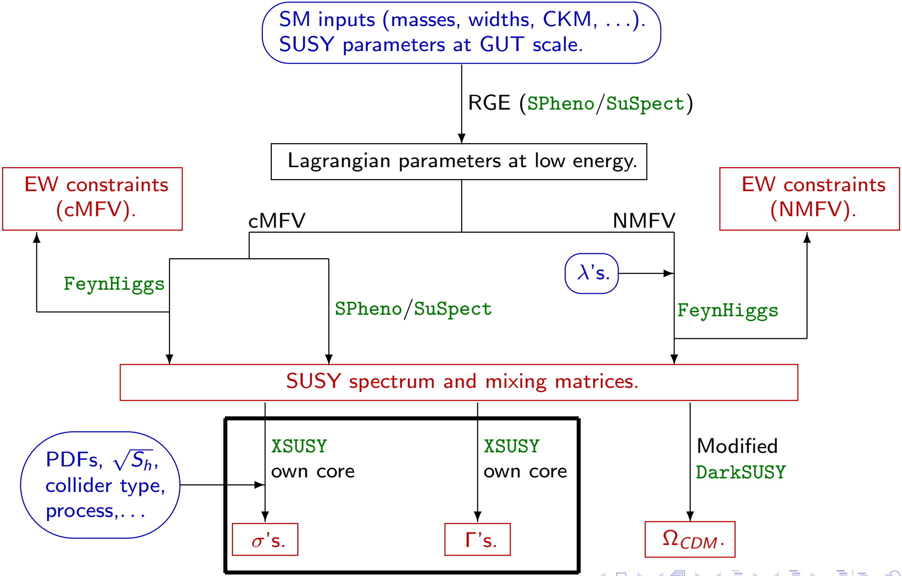
Outline

The XSUSY approach

Current version: XSUSY 1.8.0 [BF, *in preparation*]

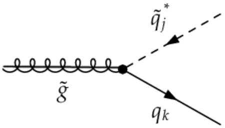
- Evolution from the GUT scale to the EW scale in cMFV:
  - SPheno or SuSpect.
- SUSY spectrum and mixing matrices:
  - FeynHiggs (NMFV).
  - FeynHiggs, SPheno or SuSpect (cMFV).
- Low-energy and electroweak constraints:
  - FeynHiggs (NMFV and cMFV).
- Dark matter relic density (NMFV and cMFV):
  - Modified DarkSUSY.
- Production cross sections and decay widths:
  - Own XSUSY core (NMFV and cMFV).

Scheme of the program



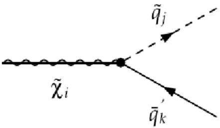
NMFV couplings

- Flavour violating couplings: $\tilde{q}-q-\tilde{\chi}$, $\tilde{q}-q-\tilde{g}$, $\tilde{q}-q-\phi$, and $\tilde{q}-\tilde{q}-V$.
- Example 1: squark-quark-gluino coupling



* MSSM: non zero coupling
  $\Leftrightarrow$ same squark and quark flavour,
  $\Leftrightarrow$ proportional to $\cos\theta_{\tilde{q}}$, $\sin\theta_{\tilde{q}}$.
* NMFV SUSY:
  $\Leftrightarrow$ proportional to R^q_{jk}, $R^q_{j(k+3)}$.

- Example 2: squark-quark-chargino coupling



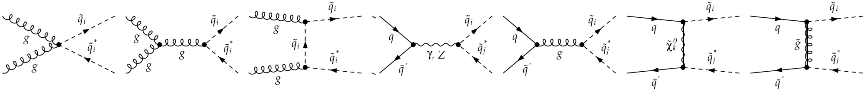
* Sum over the squark flavour content,

$$L_{\tilde{u}_j d_k \tilde{\chi}_i^\pm} = \sum_{l=1}^{3}\left[V_{i1}^* R^u_{jl} - \frac{m_{u_l}\, V_{i2}^*\, R^u_{j(l+3)}}{\sqrt{2}\, m_W \sin\beta}\right] V_{u_l d_k}\,,$$

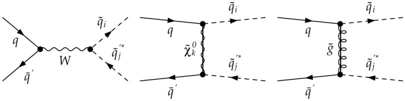
$$-R^*_{\tilde{u}_j d_k \tilde{\chi}_i^\pm} = \sum_{l=1}^{3} \frac{m_{d_k}\, U_{i2}^* V_{u_l d_k}^*\, R^{u*}_{jl}}{\sqrt{2}\, m_W \cos\beta}\,.$$

Cross sections (1)

- Squark-antisquark pair production
  - * Neutral current



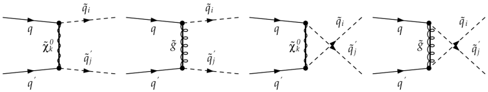
  - * Charged current



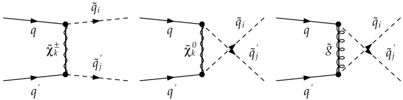
  - * All LO QCD and EW diagrams.
  - * Remark: gluon-squark-squark vertex is flavour conserving.
  - * Compact expressions for cross sections $\Rightarrow$ form factors.

Cross sections (2)

- Squark-squark pair production
  - * Same isospin (two up- or two down-type squarks)



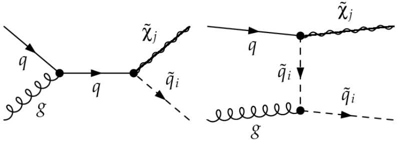
  - * Different isospin (one up-type and one down-type squark)



  - * Possible heavy flavour production with light flavours in the initial state.
  - * Large quark-quark luminosity at the LHC.

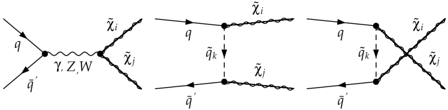
Cross sections (3)

- Associated gaugino-squark production



  * Semi-weak process plus light gaugino $\Rightarrow$ rather large cross sections.
  * Flavour violating effects at the weak vertices.

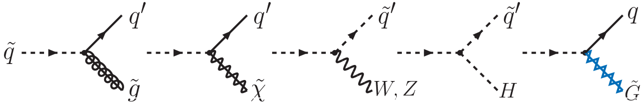
- Gaugino pair production



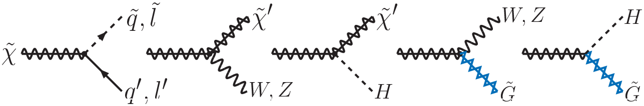
  * Sum over all squark mass-eigenstates $\Rightarrow$ reduced flavour violating effects.

2-body decay widths

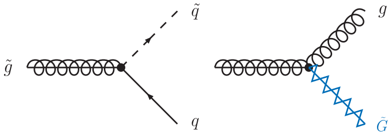
- Squark decays



- Gaugino decays



- Gluino decays



Outline

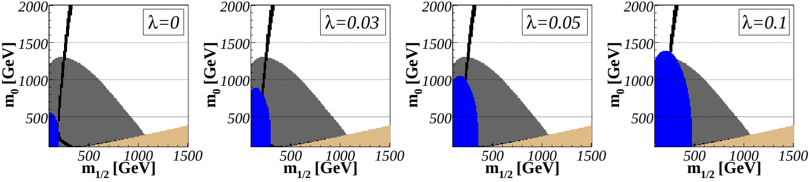
Simplified NMFV scenario

- The squared squark mass matrices are approximated

$$M^2_{\tilde{Q}} = \begin{pmatrix} M^2_{LL,1} & 0 & 0 & m_1\, m_{LR,1} & 0 & 0 \\ 0 & M^2_{LL,2} & \lambda M_{LL,2} M_{LL,3} & 0 & m_2\, m_{LR,2} & 0 \\ 0 & \lambda M_{LL,2} M_{LL,3} & M^2_{LL,3} & 0 & 0 & m_3\, m_{LR,3} \\ m_1\, m_{RL,1} & 0 & 0 & M^2_{RR,1} & 0 & 0 \\ 0 & m_2\, m_{RL,2} & 0 & 0 & M^2_{RR,2} & 0 \\ 0 & 0 & m_3\, m_{RL,3} & 0 & 0 & M^2_{RR,3} \end{pmatrix} .$$

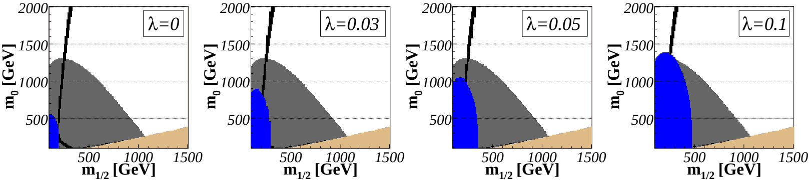
- One single parameter $\lambda \leq 0.1$ (both for up-type and down-type sectors).
- Satisfy constraints from FCNC.

mSUGRA parameter space analysis (1)



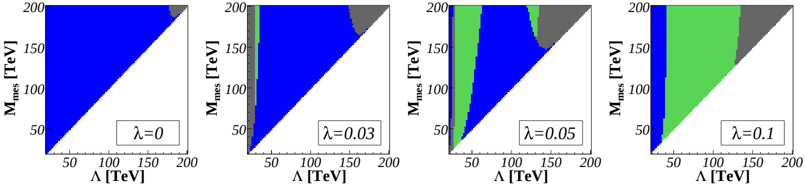
- $\tan\beta = 10, \mu > 0, A_0 = 0$ GeV, $0 \leq \lambda \leq 0.1$. [Bozzi, BF, Herrmann, Klasen (2007)]
- Region favoured by a_μ @2σ (grey)
  - * $a_\mu^{\rm SUSY} = (22 \pm 10) \times 10^{-10}$ (BNL data vs SM) [PDG (2006)].
  - * Squarks contribute at the two-loop level only.
    $\Rightarrow$ Reduced squark vs. slepton one-loop contributions.
- Region excluded by $b \to s\gamma$ @2σ (blue)
  - * $\mathrm{BR}(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ [Barbiero *et al.* (2006)].
  - * NMFV contributes at the one-loop level (same as the SM contributions).
    $\Rightarrow$ Very sensitive to λ.
- Region excluded by $\Delta\rho$ @2σ (not shown)
  - * $\Delta\rho = 0.00102 \pm 0.00086$ (fits of EWPO) [PDG (2006)].
  - * Sensitive to squark mass splitting [Veltman (1977)], influence on m_W, $\sin^2\theta_W$.
  - * Very heavy scalar and gaugino masses excluded.

mSUGRA parameter space analysis (2)



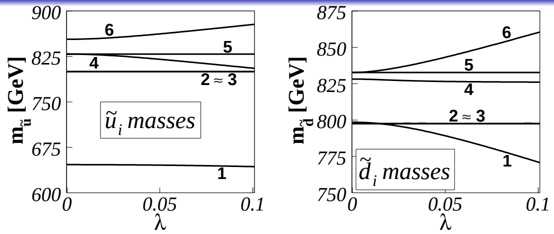
- $\tan\beta = 10, \mu > 0, A_0 = 0$ GeV, $0 \leq \lambda \leq 0.1$. [Bozzi, BF, Herrmann, Klasen (2007)]
- Charged LSP (beige)
  - * DM candidate $\Leftrightarrow$ Color singlet and electrically neutral [Ellis *et al.* (1984)].
- Region favoured by Ω_{CDM} (black)
  - * $0.094 < \Omega_{CDM}\, h^2 < 0.136$ [Hamann, Hannestad, Sloth, Wong (2007)] (WMAP, SDSS, SNLS, Baryon Acoustic Oscillations).
  - * Not really sensitive to λ (many involved processes).

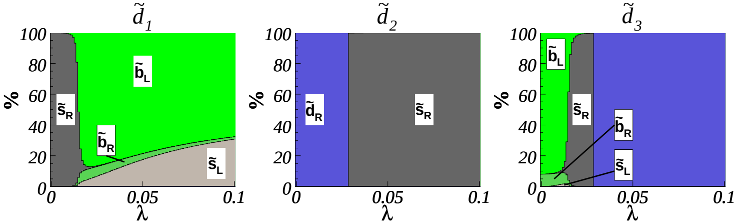
GMSB parameter space analysis



- $\tan\beta = 15, \mu > 0, N_{\rm mes} = 3, 0 \leq \lambda \leq 0.1$. [BF, Herrmann, Klasen (*in prep.*)]
- Region excluded by $b \to s\gamma$ @2σ (blue)
  - * $\mathrm{BR}(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ [Barbiero *et al.* (2006)].
  - * NMFV contributes at the one-loop level (same as the SM contributions). $\Rightarrow$ Very sensitive to λ.
  - * cMFV scenarios excluded, but windows open at large λ.
- Region favoured by a_μ @2σ (green)
  - * $a_\mu^{\rm SUSY} = (22 \pm 10) \times 10^{-10}$ (BNL data vs SM) [PDG (2006)].
  - * Squarks contribute at the two-loop level only. $\Rightarrow$ Reduced squark vs. slepton one-loop contributions.

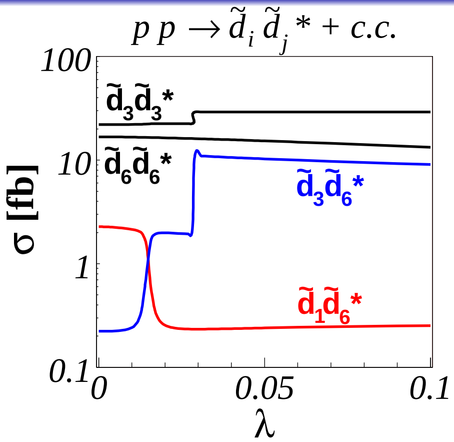
Benchmark point BFHK-B: flavour content





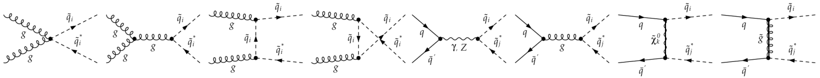
- Hermitian squark mass matrices depend continuously on the single parameter λ.
  - The eigenvalues do not cross $\Rightarrow$ avoided crossings.
  - Exchange of the flavour content between the concerned eigenstates.
- Large mixing between $2^{\rm nd}$ and $3^{\rm rd}$ generations, even for small λ.

BFHK-B: neutral current squark-antisquark pair production

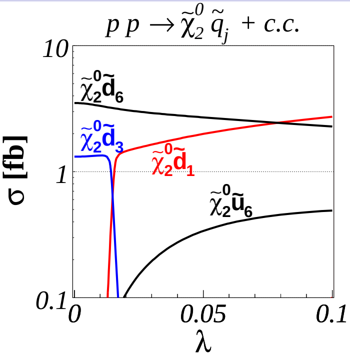


[Bozzi, BF, Herrmann, Klasen (2007)]

- Diagonal pairs:
  - Gluon-fusion initiated diagrams.
  - Strong production
    $\Rightarrow$ Large cross sections.
  - Quite unsensitive to λ
    (flavour-independent $g\tilde{q}\tilde{q}$ vertex).
- Non-diagonal pairs:
  - Only $q\bar{q}$ annihilation diagrams
    (EW + heavy gluino).
  - Show sharp transitions with λ
    (Avoided crossings - mass flips).
    Example: $\tilde{d}_1\tilde{d}_6^*$ and $\tilde{d}_3\tilde{d}_6^*$

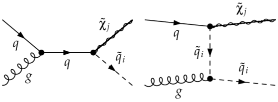


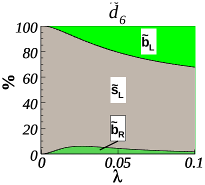
BFHK-B: associated squark-neutralino production

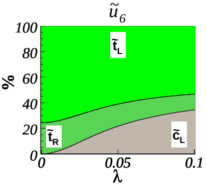


[Bozzi, BF, Herrmann, Klasen (2007)]

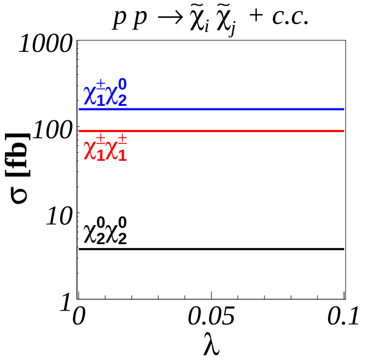
- Semi-strong production (10^{-1} fb to 10^2 fb).
- Quite sensitive to flavour violation (due to the $q\tilde{q}\tilde{\chi}$ vertex).
- $\tilde{d}_1$-$\tilde{d}_3$ mass flip.
- $\tilde{d}_6\tilde{\chi}^0_2$ cross section decreases with λ (see $\tilde{d}_6$ strange/bottom content).
- $\tilde{u}_6\tilde{\chi}^0_2$ cross section increase with λ (see $\tilde{u}_6$ charm/top content).





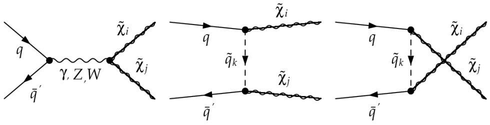


BFHK-B: gaugino-pair production

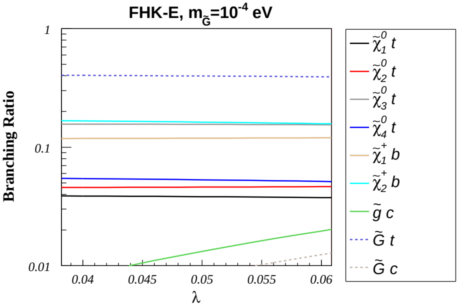


- Light gauginos
  (rather large cross sections).
- Insensitive to flavour violation
  (sum over all the squark physical states).

[Bozzi, BF, Herrmann, Klasen (2007)]



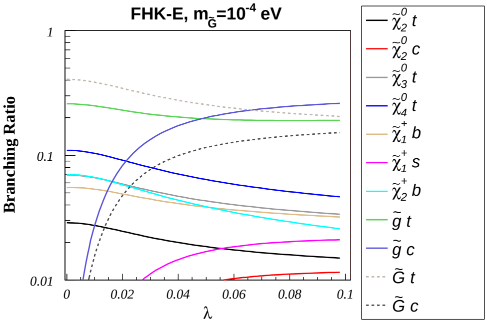
FHK-E: lightest $\tilde{u}_1$ decays



[BF, Herrmann, Klasen (*in prep.*)]

- NMFV GMSB scenario: mainly stop $\tilde{u}_1$, with a small scharmed component.
- Lightest quark decays mainly into gravitino and top quark.
- At intermediate λ, sizeable charm decay channels.
- Small dependence on λ.

FHK-E: heavier $\tilde{u}_6$ decays



[BF, Herrmann, Klasen (*in prep.*)]

- NMFV GMSB scenario (extended λ range shown here).
- Mainly stop $\tilde{u}_6$, with a small scharmed component
- Strong dependence on λ.
- Preferred channels: $\tilde{G}$ and $\tilde{g}$.

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Conclusion and outlook

- XSUSY is a multipurpose program to study NMFV effects in SUSY models.
  - Interface with DarkSUSY, FeynHiggs, SPheno and SuSpect.
  - mSUGRA, GMSB and AMSB scenarios implemented.
  - Allows for a detailed analysis of the NMFV parameter space.
  - Allows for a detailed analysis od the squark sector flavour structure.
  - Contains production cross sections at LO for “all” sparticle pair-production processes.
  - Contains SUSY particle two-body decays at LO.
- To do list:
  - Next-to-leading order
  - Three-body decays.
  - Full experimental study
    (heavy-flavour tagging efficiencies, detector resolutions, background,...)
    $\Rightarrow$ complete understanding of flavour violating effects.
    $\Rightarrow$ proposal of experimental signatures for NMFV SUSY models.

Appendix

Appendix

Minimal flavour violation (in the squark sector)

[Buras, Gambino, Gorbahn, Jager, Silvestrini (2001); D'Ambrosio, Giudice, Isidori, Strumia (2002); Altmannshofer, Buras, Guadagnoli (2007)]

- Flavour-violating terms of the Lagrangian:
  * Rewritten as functions of the Yukawa couplings.
  * Not set to zero as for cMFV.
  - Flavour structure generated by the Yukawa couplings
    $\equiv$ different renormalizations of the quark and squark mass matrices.
    $\Rightarrow$ Additional flavour violation at the weak scale through RG running.

- The squared squark mass matrices are

$$M^2_{\tilde{Q}} = \begin{pmatrix} M^2_{LL,1} & \Delta^{12}_{LL} & \Delta^{13}_{LL} & m_1\, m_{LR,1} & \Delta^{12}_{LR} & \Delta^{13}_{LR} \\ \Delta^{21}_{LL} & M^2_{LL,2} & \Delta^{23}_{LL} & \Delta^{21}_{RL} & m_2\, m_{LR,2} & \Delta^{23}_{LR} \\ \Delta^{31}_{LL} & \Delta^{32}_{LL} & M^2_{LL,3} & \Delta^{31}_{RL} & \Delta^{32}_{RL} & m_3\, m_{LR,3} \\ m_1\, m_{RL,1} & \Delta^{12}_{RL} & \Delta^{13}_{RL} & M^2_{RR,1} & \Delta^{12}_{RR} & \Delta^{13}_{RR} \\ \Delta^{21}_{LR} & m_2\, m_{RL,2} & \Delta^{23}_{RL} & \Delta^{21}_{RR} & M^2_{RR,2} & \Delta^{23}_{RR} \\ \Delta^{31}_{LR} & \Delta^{32}_{LR} & m_3\, m_{RL,3} & \Delta^{31}_{RR} & \Delta^{32}_{RR} & M^2_{RR,3} \end{pmatrix}$$

- The off-diagonal elements depend only on the Yukawa couplings.
- The diagonalizing matrices depend only on the CKM matrix.